LCA Methodology

Allocation of Environmental Burdens in Co-product Systems: Process and Product-related Burdens (Part 2)

Adisa Azapagic and Roland Clift

School of Engineering in the Environment, University of Surrey, Guildford, Surrey, GU2 5XH, UK

Corresponding author: Adisa Azapagic; e-mail: a.azapagic@surrey.ac.uk

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Abstract. ISO 14041 requires that allocation by physical causality must reflect the quantitative changes in product outputs or functions and will not necessarily be in proportion to simple physical measure such as mass. This paper examines the instances where physical causality can be represented by mass. However, it also goes further than ISO to demonstrate that the type of causality in the system is not necessarily always the same and can change depending on the way the system is operated. Whole system modelling and the marginal allocation approach are used to identify the correct type of causality for different operating states of the system and the corresponding changes in the environmental burdens. This is generally not possible with the other allocation methods, also examined in this paper. Both process- and product-related burdens are considered and the approach is illustrated by a reference to an existing system producing five boron co-products.

Keywords: Allocation; boron; environmental impacts; LCA; Life Cycle Assessment; linear programming; marginal values; system analysis

1 Introduction

ISO 14041 (1998) set guidelines for dealing with allocation in multiple-function systems. According to this procedure, allocation should be avoided where possible by system disaggregation or by expanding system boundaries. If that is not feasible, then the environmental burdens should be partitioned among different functions of the system in a way which reflects the underlying physical causality. This implies that the allocated burdens must follow the quantitative changes in product outputs or functions, which will not necessarily be in proportion to simple physical measure such as mass.

This paper focuses on allocation by physical causality, the second step in the ISO 14041 hierarchy. However, it goes further than ISO to demonstrate that the type of physical causality and, hence, the allocated burdens in a system are not necessarily fixed but can change depending on the way the system is operated. Marginal allocation and whole system modelling (Azapagic and Clift, 1998, 1999a) are used to identify the "active" or relevant physical causality and allocation parameters in the system. These considerations are illustrated by a "cradle to gate" study of an industrial multiple-function system producing boron co-products (Azapagic and Clift, 1999b).

2 Allocation in the Boron Co-product System

The Boron system, shown in **Fig. 1**, produces five products: "10 Mol" borate (10 Mol), "5 Mol" borate (5 Mol), boric acid (BA), anhydrous boric acid (ABA) and anhydrous borax (AB). 5 and 10 Mol are produced from borax and kernite; BA is produced from kernite only. ABA and AB are made from 5 Mol and BA, respectively. A more detailed description of this system is given in Azapagic and Clift (1999b).

There were two goals of the study: to evaluate the environmental performance of the system from "cradle to grave" as a guide for environmental management; and to provide background LCA data for other systems using one or more of the boron co-products. In the first case, the functional unit is defined as "operation of the system for one year" while for the second goal the functional unit can be defined either

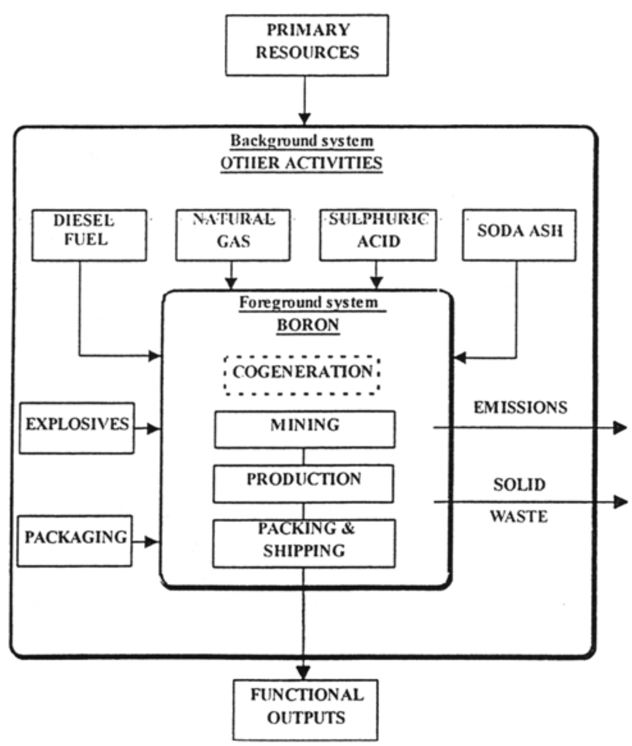

Fig. 1: LCA flow diagram of the boron system

as "1000 kg of each product" or "1000 kg of B_2O_3 equivalent" (Azapagic and Clift, 1999c). For the purposes of discussion here, the functional unit is taken to be the "operation of the system for one year" and is represented by the total annual output of the five boron products of 1,064,620 tonnes.

2.1 Allocation as a function of the operating state of the system

In the boron system the outputs of the different co-products can be varied independently, so that physical causality can be used as a basis for allocation (Azapagic and Clift, 1999a; ISO, 1998). In this particular case, physical causal relationships are modelled mathematically by Linear Programming (LP) (Azapagic and Clift, 1999c); however, the discussion here is independent of the details of the mathematical model.

The specific allocation case developed in Part 1 of this paper (Azapagic and Clift, 1999c) refers to short-term marginal changes in the operation of the system, including marginal variations in the co-product outputs. This part of the paper, in addition to marginal, also considers incremental changes to show how the allocated burdens can vary when the operation of the system is shifted to a new operating point. An example would include an incremental change in one or more of the functional outputs or in a capacity of the process. LP enables analysis of both marginal and incremental changes in the system. Analysis of average changes, i.e. a major shift in the operation of the system can also be modelled by LP, provided that non-linearities in the system can be expressed in a linear form.

As in Part 1, a distinction is made here between product- and process-related burdens. The product-related burdens depend on product outputs, while the process parameters are related to the capacity of product dryers and heat requirement in the process. Product-related parameters are relevant for providing LCA data for users of one of the co-products, or for guiding environmental management of the entire product system (Azapagic, 1996; Clift et al., 1998); process-related parameters are mainly of interest for environmental management and life cycle design of the facility itself. Marginal changes in product-related burdens are discussed in Azapagic and Clift (1999c). Process- and product-related burdens and their change with the operating state of the system are illustrated in the section below.

In order to illustrate changes in the "active" causal relationships and therefore in the allocated burdens with the operating conditions of the system, two distinct cases are considered. The first examines changes in the state of the system resulting from changes in the product-related burdens, represented by the ratio of kernite to borax ore used for production of 5 Mol and 10 Mol borates. Since the interest here is in the analysis of changes in the burdens and impacts with product outputs for different ore ratios, the burdens are considered to be product-related. In the second example, changes in the burdens are caused by process-related parameters, here represented by the capacity of the dryer for 5 Mol and the total heat requirement in the system.

2.1.1 Product-related burdens

In this example, the ratio of kernite to borax ore (K/B) is varied from 0.150 to 0.450 and compared with the current ratio of 0.205. Because kernite contains a greater proportion of B_2O_3 then borax, changing their ratio is expected to cause the following changes in the operating state of the system. With increased kernite to borax ratio, less ore will be required in the production process which will, therefore, reduce the mining activities and the related environmental burdens. Furthermore, the ratio of the borates to insolubles in the dissolvers and thickeners will change, causing changes in their operating conditions. These will, in turn, change the environmental burdens from the system, i.e. solid waste, energy requirements, etc. However, these changes will directly affect only those products for which the ore mix is a variable of the process, i.e. 5 Mol and 10 Mol. It is also expected that, because the processing route to AB involves 5 Mol, the burdens allocated to AB will change. The marginal burdens of BA and ABA should remain the same for all K/B ratios because borax ore is not involved in their production.

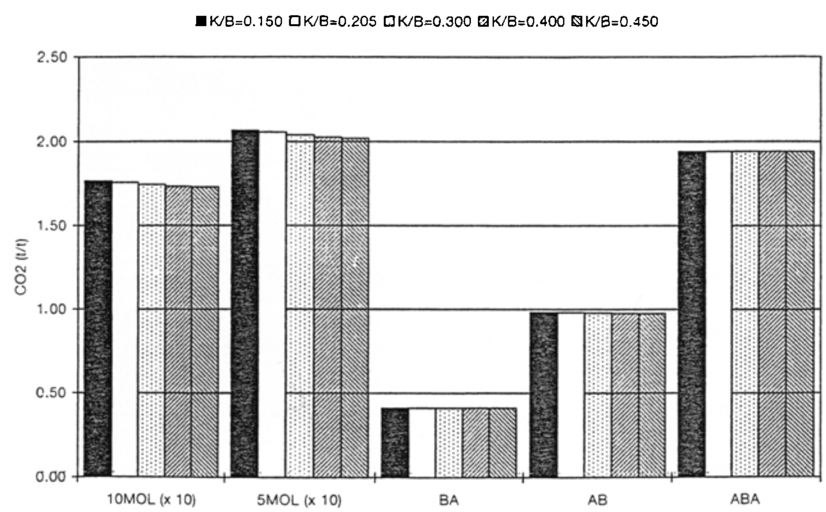

Fig. 2: Allocated CO_2 emissions for different operating states of the system

For illustration, the allocated emissions of CO_2 for different K/B ratios are considered. The results in **Fig. 2** show that only the allocation coefficients for 5 Mol and 10 Mol change: with an increase in the kernite to borax ratio, the burdens allocated to 5 Mol and 10 Mol decrease, thus causing a decrease in the total emissions of CO_2 from the system. Related to the change in the burdens for 5 Mol is also the change in the burdens allocated to AB. However, as expected, the burdens allocated to ABA and BA remain unchanged.

A similar kind of analysis applies to the other mining-related activities, for instance, the consumption of diesel fuel. By increasing K/B from 0.15 to 0.45, the fuel consumption allocated to the 5 Mol and 10 Mol decreases by, on average, 5% (→ *Fig. 3*), which is associated with a decrease of 4% in the total consumption of fuel in the mine. Reduction in oil consumption means reduced environmental burdens; however, it also means reduced production costs. Thus, whole system modelling, in addition to solving the problem of allocation of environmental burdens, has other practical implications, such as identifying places for improvement of both environmental and economic performance (AZAPAGIC and CLIFT, 1998, 1999d).

both product- and process-related when changes in both parameters are of interest. A case in which the burdens are only process-related is discussed later in this paper. The results of marginal allocation are compared with other allocation methods commonly used by LCA practitioners: mass and market value.

To show the differences in the burdens associated with different packaging used for the products, the product outputs have been differentiated into nineteen different categories (→ *Table 1*). As an illustration, the process-related parameters are represented by the capacity of the rotary dryer for 5 Mol and the total heat requirement in the system. For the mathematical formulation, see Part 1 of this paper (AZAPAGIC and CLIFT, 1999c). Although the allocation results are shown for the emissions of CO_2 only, similar observations apply to the other burdens and impacts in the system.

Suppose that the interest is now to analyse changes in the burdens with changes in both the outputs of the co-products and the processing capacity of the rotary dryer, in a system where these parameters can be changed independently. This would exclude, for example, analysis of the system in which the rotary dryer is already working at maximum throughput (i.e. production of 5 Mol cannot be increased). This type of calculation is relevant where the operation of the system is not only determined by product demand but also by plant capacities, and would be used in practice for detailed life cycle process design or to evaluate the implications of plant capacity expansion.

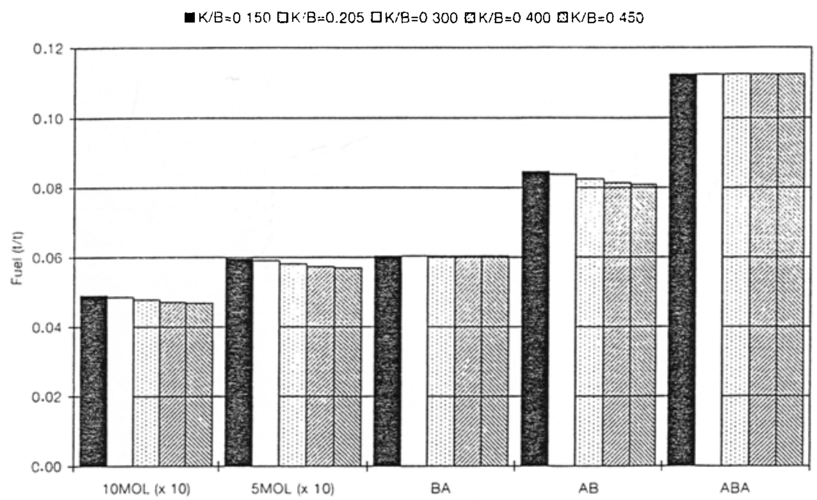

Fig. 3: Allocated fuel consumption for different operating states of the system

Although the preceding section considered the effects of changes in the system operating conditions, the changes in the burdens remained product-related. The "active" causality in both examples, identified through whole system modelling, is mass flow. The same results are obtained if allocation is based on mass when system is disaggregated (see AZAPAGIC and CLIFT, 1999c). Thus, in these cases, physical quantity is a relevant allocation parameter. However, the results are quite different when the burdens change to become process-related, as demonstrated in the following section.

2.1.2 Product- and Process-related burdens

The examples presented so far concerned changes in the burdens with the product-related parameters such as output of co-products. This section examines how the burdens allocated solely to the products can change to become

The results of marginal allocation for these conditions are shown in **Table 1** and **Fig. 4** (Case 2). When compared with the product-related burden in Case 1, where the total CO_2 emissions are allocated among the co-products (for more detail see Azapagic and Clift, 1999c), it is apparent that only emissions allocated to 5 Mol from the rotary dryer change, decreasing on average by 30%, while CO_2 emissions allocated to the other products remain the same. In addition, as the capacity constraint now determines the operation of the system, the burden allocated to the rotary drier changes from

Table 1: Changes in the allocated CO_2 emissions with the state of the system

		Allocation coefficients, $\lambda_{CO2,c}$ (t CO_2/t)					
Product- and process-related parameters	**Output, e_c (t/yr)**	**Case 1: Product-related burden**	**Case 2: Product- & process-related**	**Case 3: Product- & process-related**	**Case 4: Product- & process-related**	**Case 5: Product- & process-related**	**Case 6: Process-related burden**
10Mol-bulk	24419	0.156	0.156	0.033	0.033	0.033	0.000
10Mol-25kg bags[a]	26276	0.192	0.192	0.069	0.069	0.069	0.000
10Mol-50kg bags[b]	16544	0.189	0.189	0.066	0.066	0.066	0.000
10Mol-PP bags	13965	0.165	0.165	0.042	0.042	0.042	0.000
10 Mol – average	**81204**	**0.176**	**0.176**	**0.052**	**0.052**	**0.052**	**0.000**
Penta[c]-bulk	90959	0.247	0.247	0.032	0.033	0.032	0.000
5Mol-bulk	653860	0.177	0.114	0.044	0.000	0.042	0.000
5Mol-25kg bags	27014	0.212	0.150	0.080	0.000	0.077	0.000
5Mol-50kg bags	32052	0.209	0.146	0.076	0.000	0.073	0.000
5Mol-PP bags	9754	0.184	0.121	0.051	0.000	0.049	0.000
5 Mol – average	**813639**	**0.206**	**0.156**	**0.057**	**0.007**	**0.055**	**0.000**
BA-bulk	72065	0.395	0.395	0.165	0.165	0.165	0.000
BA-25kg bags	25408	0.431	0.431	0.201	0.201	0.201	0.000
BA-50kg bags	11271	0.427	0.427	0.198	0.198	0.198	0.000
BA-PP bags	39362	0.404	0.404	0.174	0.174	0.174	0.000
BA – average	**148106**	**0.414**	**0.414**	**0.185**	**0.185**	**0.185**	**0.000**
AB-25kg bags	2428	0.991	0.903	0.025	-0.048	0.021	0.000
AB-50kg bags	9264	0.987	0.898	0.021	-0.052	0.017	0.000
AB-PP bags	4728	0.962	0.873	-0.005	-0.077	-0.008	0.000
AB – average	**16420**	**0.980**	**0.891**	**0.014**	**-0.059**	**0.010**	**0.000**
ABA-25kg bags	2020	1.955	1.955	0.227	0.227	0.227	0.000
ABA-50kg bags	2137	1.952	1.952	0.224	0.224	0.224	0.000
ABA-PP bags	1100	1.918	1.918	0.190	0.190	0.190	0.000
ABA – average	**5257**	**1.942**	**1.942**	**0.214**	**0.214**	**0.214**	**0.000**
Capacity	786350	0.000	0.059	-0.002	0.042	0.000	-0.047
Heat	2.35E+08[d]	0.000[e]	0.000[e]	7.93E-04[e]	7.93E-04[e]	7.93E-04[e]	13.64E-04[e]
Total CO_2 (B_{CO2})[f]		**252920**	**252920**	**252920**	**252920**	**252920**	**252920**

[a] paper bags; [b] polypropylene bags (1 tonne); [c] Penta is another name for 5 Mol which is produced in the fluid bed dryer, to distinguish it from 5 Mol produced in the rotary dryer; [d] TJ/yr; [e] tCO_2/TJ; [f] Total CO_2 for each case is calculated as: $B_{CO2}=\Sigma e_c \lambda_{CO2,c}$

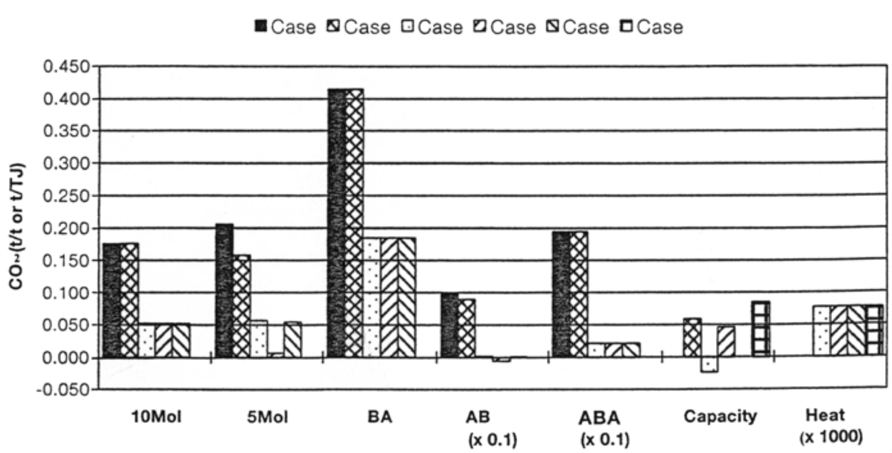

Fig. 4: Process- and product-related burdens in the boron system

zero to 0.059 t of CO_2/t. This indicates that if the throughput capacity of the drier is increased by 1 tonne, the emission of CO_2 will increase by 0.059 tonne. Hence, the allocated marginal burdens have changed from Case 1, where they were fully allocated to the product, to be shared between the products and the capacity of the dryer in Case 2. The total burden has, however, remained the same and the sum of the allocated burdens is again equal to the total unallocated burdens (ISO, 1998).

The fact that a proportion of the burden which in Case 1 was allocated to 5 Mol is now transferred to the capacity of the dryer is not surprising because the capacity is a process parameter related to the production of 5 Mol. However, without whole system modelling, it is not possible to determine the proportion in which the allocation should be made. In allocation by mass without system disaggregation, the emissions would be partitioned in equal proportions among all product- and process-related parameters to give an allocation factor of 0.137 t/t (total CO_2 emissions of 252920 t/yr divided by the sum of the total product output of 1,064,620 t/yr and the capacity of the dryer of 786350 t/yr). This differs considerably from the marginal allocation coefficients with the highest difference of 93% for ABA (the allocation coefficient in *Table 1* for ABA in Case 2 is 1.942 tCO_2/t). If, on the other hand, the burden is allocated by mass when the system is disaggregated (see AZAPAGIC and CLIFT, 1999c), the results correspond to the marginal allocated burdens obtained by whole system modelling. This confirms that the "active" causality in the system has not changed and allocation by mass (with disaggregation) is still appropriate.

Allocation by market value is not possible in this case because there is no market that can attach financial value to process burdens. This is one of the reasons why allocation on the basis of market value should not be used in systems where physical causality exists.

Consider now a case where, in addition to the product demand and capacity of the rotary dryer, system operation is determined by heat requirements. The marginal allocated burdens are, as shown in **Table 1** and **Fig.** 4 (Case 3), quite different from those obtained in the previous two cases: all product-related emissions decrease, on average by 56%, and the heat-related burden is now equal to 7.39E-04 t/TJ. This is perhaps to be expected: the heat constraint is related to all products so that by allocating some of the burden to it, the contribution of the products to the total emissions should change. However, the character of the change is more interesting: the relative contributions of the products are no longer the same and 5 Mol now contributes to the total CO_2 emissions more than AB. Furthermore, by contrast with the preceding two cases, 5 Mol produced in the rotary dryer has higher allocated burden than 5 Mol (Penta) produced in the fluid bed dryer. Finally, the burdens allocated to AB packed in polypropylene (PP) bags and to the capacity constraint are negative, indicating that increasing either the AB output or capacity by one tonne would in fact decrease the emissions of CO_2 by 5 and 2 kg, respectively.

Similar results are obtained if the system is again subject to the same constraints, but where production of 5 Mol from the rotary dryer is not limited by market demand and can vary according to the process requirements. This means that at the solution of the LP model the marginal burdens associated with 5 Mol are zero (Case 4 in *Table 1*). The interpretation of these results is that production of 5 Mol can increase by a marginal amount with no effect on the total CO_2 emissions. In addition, since the burdens allocated to all AB products are negative, a unit increase in either of the AB products will cause an average decrease in CO_2 of 0.06 tonnes. Thus, for this state of the system, it would be better from the environmental point of view to increase the production of AB or perhaps 5 Mol, while keeping other outputs constant. In this way whole system modelling can guide the environmental management of the processing and product systems by indicating places for improvements (AZAPAGIC, 1996; AZAPAGIC and CLIFT, 1998, 1999b,d). It may also be noted that the burden allocated to the capacity has changed from a negative value in Case 3 to a positive value of 0.042 t CO_2/t.

Furthermore, if the state of the system changes to become constrained only by the product output and heat demand, the allocated burdens change again. As shown in **Table 1** for Case 5, average contributions of both 5 Mol and AB to the total CO_2 increase to 0.055 t/t and 0.010 t/t, respectively. The burden allocated to the capacity constraint is zero, while all other burdens are unchanged. It may be noted here again that the CO_2 is fully allocated among the product- and process-related parameters.

2.1.3 Process-related burdens

Finally, in cases where the interest lies in the effect on the burdens of changes in the capacity and heat constraints, while maintaining the same product output, the CO_2 emissions are allocated to these two process parameters and the emissions are no longer related to the products (→ *Table 1*, Case 6). Thus, the burden allocated to the capacity of the rotary dryer changes from zero in the previous case to -0.047 t/t, while the heat burden increases from 7.39E-04 to 13.64E-04 t/TJ. Moreover, in addition to these two constraints, other process-related constraints (not shown in the Table) also determine the operation of the system. For instance, the capacity of the 10 Mol dryer and the availability of boron ore now also limit the operations; their marginal values are equal to -0.103 and -0.169 t/t, respectively. This means that the burdens have become solely process-related because the state of the system is now determined by a different set of active constraints. Without system modelling, it is usually not possible to know which constraints will be active at the solution nor in which proportion the burdens should be allocated to the process parameters.

2.1.4 Final considerations

The results shown in **Table 1** for Cases 2-6 illustrate how the environmental burdens change with the state of the system, as defined by which constraints are active: the allocated burdens are not fixed but change to reflect changes in the system parameters that determine its operation. Since the effect on the burdens of changes in the parameters is a direct consequence of the type of causality "active" in the

system, the question is: are changes in the state of the system associated with a change in the causality and how can this be detected? The answer is obtained by comparing the marginal allocation results for these cases with allocation on the mass basis with disaggregation. It was demonstrated above that physical causality is represented by mass when the system is disaggregated, with the allocated burdens the same as those obtained by marginal allocation. However, analysis of Cases 3 to 6 demonstrates that the same causality principle is no longer valid when the state of the system is defined by a mixture of process- and product-related parameters; causality is now too complex to be represented by a simple physical quantity, such as mass.

3 Conclusions

Because of the complex interactions among different parts of the product system, the kind of causality governing system behaviour and the resulting allocation coefficients cannot be identified without whole system modelling. The allocated burdens depend on the state of the system, which in turn depends on which constraints are active. As shown in these examples, the active constraints cannot normally be identified without a system model. This demonstrates the value of whole system modelling: by accounting for the complex relationships among different parts of the system, it can determine the type of the causality in the system and allocate the burdens accordingly. In addition, whole system modelling can indicate places in the system where process improvements can be made and thus aid the environmental system management.

4 References

AZAPAGIC, A. (1996): Environmental System Analysis: The Application of Linear Programming to Life Cycle Assessment. PhD Dissertation, University of Surrey, Guildford, UK

AZAPAGIC, A.; CLIFT, R. (1998): Linear Programming as a Tool in Life Cycle Assessment. Int. J. LCA 3(6) 305-316

AZAPAGIC, A.; CLIFT, R. (1999a): Allocation of Environmental Burdens in Multiple-function Systems. J. Cleaner Prod. 7(2) 101-119

AZAPAGIC, A.; CLIFT, R. (1999b): Life Cycle Assessment as a Tool for Improving Process Performance: A Case Study on Boron Products. Int. J. LCA 4(3) 133-142

AZAPAGIC, A.; CLIFT, R. (1999c): Allocation of Environmental Burdens in Co-product Systems: Product-related Burdens (Part 1). Int. J. LCA 4(6) 357-369

AZAPAGIC, A.; CLIFT, R. (1999d): Life Cycle Assessment and Multiobjective Optimisation. J. Cleaner Prod. 7(2) 135-143

CLIFT, R. et al. (eds.) (1998): Toward a Coherent Approach to Life Cycle Inventory Analysis Report of the Working Group on Inventory Enhancement. SETAC-Europe. (Summary available in SETAC Newsletter, Vol. 10, Issue 3, pp 14-20, May 1999, Brussels)

ISO 14041 (1998): Environmental Management – Life Cycle Assessment: Goal and Scope Definition and Inventory Analysis

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